THE JOHN CALVIN McNAIR LECTURES

TIME, MATTER, AND VALUES

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TIME, MATTER, AND VALUES

BY

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THE McNAIR LECTURES

The John Calvin McNair Lectures were founded through a bequest made by Rev. John Calvin McNair, of the class of 1849. This bequest became available to the University in 1906. The extract from the will referring to the foundation is as follows:

"As soon as the interest accruing thereon shall by said Trustees be deemed sufficient they shall employ some able Scientific Gentleman to deliver before the students then in attendance at said University, a course of lectures, the object of which lectures shall be to show the mutual bearing of science and theology upon each other, and to prove the existence and attributes, as far as may be, of God from nature. The lectures, which must be performed by a member of some one of the Evangelic denominations of Christians, must be published within twelve months after delivery, either in pamphlet or book form."

PREFACE

THE following pages represent the author's attempt to give in very brief form some of the most significant changes in fundamental concepts which have resulted from the extraordinary advances made in recent years in the field of experimental physics. These changes obviously have important bearings not only on physics but on the whole outlook of mankind toward nature, and hence toward life. They show that the great blunder which the physics of the past has made has consisted in extending its generalizations with undue assurance into fields in which they have not been experimentally tested,—that is, in treating these generalizations as fixed, *universally* applicable principles instead of as essentially working hypotheses. This has led in the past to a dogmatism in science which is at bottom indistinguishable from dogmatism in

theology or in any other field; for dogmatism in any field is merely assertiveness without knowledge. But the physicist has recently, through his blunders and his new experimental findings, learned a lesson of open-mindedness which cannot fail to influence other fields of thought. Philosophy and theology, as well as biology and psychology, are sure to profit from it.

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CHAPTER I

NEW IDEAS ABOUT TIME

TO THE ordinary modern man nothing is simpler than the idea of time. He had a Waterbury watch for a Christmas present by the time he was six. He timed horse races or hundred-yard dashes or bicycle speeds to a fifth of a second with a stop watch before he was twelve. Through all his life he has gone to classes, eaten his meals, caught his trains—or missed them—by the clock. To him, therefore, time is a perfectly simple, completely understood, common sense concept which has always been with the race and always will be.

But is this complacent, common sense view of the ordinary hard-headed citizen sound or unsound? Or was, perhaps, the Mad Hatter in *Alice in Wonderland* nearer right when he said

"If you knew Time as well as I do, you wouldn't talk about wasting *it*. It's *him*."

"I don't know what you mean," said Alice.

"Of course you don't," the Hatter said, tossing his head contemptuously. "I dare say you never even spoke to Time!"

"Perhaps not," Alice cautiously replied; "but I know I have to beat time when I learn music."

"Ah! That accounts for it," said the Hatter, "He won't stand beating. Now if you only kept on good terms with him, he'd do almost anything you liked with the clock. For instance, suppose it were nine o'clock in the morning, just time to begin lessons: you'd only have to whisper a hint to Time, and round goes the clock in a twinkling! Half-past one, time for dinner!"

("I only wish it was," the March Hare said to itself in a whisper.)

"That would be grand, certainly," said Alice thoughtfully; "but then—I shouldn't be hungry for it, you know."

"Not at first, perhaps," said the Hatter; "but you could keep it to half-past one as long as you liked."

Now the question I am raising tonight is, How mad was the Hatter anyway when he gave the sort of changeable, undependable, capricious qualities to Time which we assign to personality, and, playing deliciously upon our current phrases "beating time" and "murdering time," insisted on addressing time as Him? Who is the nearer right, the Mad Hatter or the common sense citizen?

Well, at any rate, this common sense citizen hasn't always been right. Let me illustrate first how penetrating a judgment he has sometimes had by quoting from Robert Recorde's "Master and Scholar" dialogues published in the year 1556, thirteen years after the first publication of the Copernican thesis, which was: "That the earth not only moveth circularlye about his own centre, but also may be, yea and is continually out of the precise centre 38 hundredth thousand

miles." This thesis is met with the typical reaction by the scholar, who says, "Nay syr in good faith, I desire not to heare such vaine phantasies, so farre against common reason, and repugnante to the consente of all the learned multitude of Wryters, and therefore let it passe for ever, and a daye longer."

Nor, indeed, were such common sense judgments confined to the practical English, for some French verses translated in 1591, forty-eight years after Copernicus' publication similarly assert satirically,

"Those clerks that think—think how absurd a jest!
That neither heavens nor stars do turn at all,
Nor dance around this great round earthly ball,
But the earth itself, this massy globe of our's,
Turn's round about once every twice twelve hours!
And we resemble land-bred navvies
New brought aboard to venture on the seas;
Who at first launching from the shore suppose
The ship stands still and that the firm earth goes."

What are the historic facts, then, about this idea of time? Here are some of them.

Like much else in this changing world, time, *as you and I understand and use it,* is a relatively new idea, just beginning to come into use in the fifteenth and sixteenth centuries, A.D. But in order not to be misunderstood, I must explain just what I mean by the phrase "time as you and I understand and use it."

For certain limited types of purposes, time began to be, not only used, but accurately measured at the very dawn of history. Indeed the first reliable date in history, according to Breasted, was 4241 B.C., or 6173 years ago, and it is fixed by observations made in Egypt upon the star Sirius. Civilization presumably arose in Egypt, but eons before its rise, indeed from the very first appearance of life on the earth, the *day* was clearly marked by nature herself as the most fundamental, and the most simple, measure of time; for physiological processes of all sorts

in plant, insect, fish, bird, beast, and human reveal a period determined by the rising of the sun. But from that point of view that other unit, the year, has almost equal claim, for ever since "the sap began to stir in April" the return of Spring has been marked as a natural measure of time.

Now the beginnings of science are nearly always found in the first steps taken toward refining and making more precise natural but inaccurately defined concepts like those of the day and the year, and it was in this case the year rather than the day that first received in Egypt an exact quantitative definition. For the annual inundations of the Nile happened to coincide very nearly with the heliacal rising of Sirius, that is, the rising just before the dawn, so that his first appearance on the horizon in advance of the sun was taken to announce the new year, and this appearance (which, otherwise stated, marks quite accurately the annual return of the sun to a fixed point in the heavens) en-

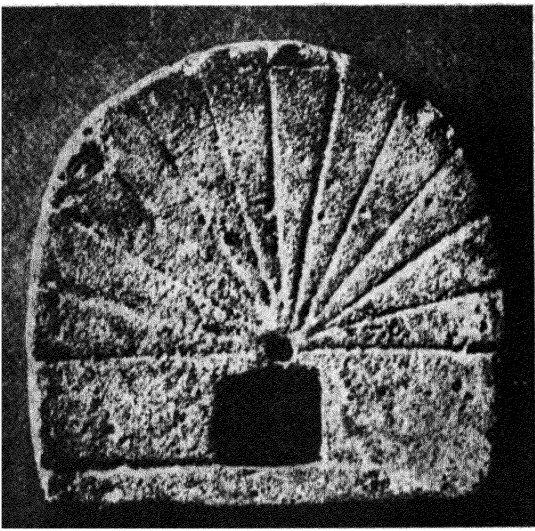

FIG. 1. *Probable Egyptian sun-dial of the period of Mernepthah. Found at Gezer in South Palestine.* From Borchardt, "*Altägyptische-Zeitmessung,*" 1920, by courtesy of the Metropolitan Museum of Art.

abled those early Egyptians in the very dawn of history to measure the duration of the year as 365 days. In the matter of the length of the year, then, there is nothing new about time at all.

Also, with the foregoing start, the Egyptians oriented their temples and pyramids so that some of them at least became time measuring instruments. For example, the Great Pyramid was so carefully placed as to serve as an instrument for the determination of the time of the equinoxes, for on these days its east and west faces were just grazed by the rays of the rising or setting sun. More than this, the Egyptians definitely had sun-dials or sun clocks, one form of which, quite like the conventional sun-dial, is shown in Figure 1, while another form is seen in Figure 2.

It will be correctly inferred from these illustrations that the modern division of the day into twelve hours, and of the hour into sixty minutes, and of the minute into sixty

seconds, comes down to us from the earliest Egyptian times. Indeed, the antiquity of the origins of both our present time-measurement-system and our angle-measurement-system is attested by the fact that these are the only surviving relics of the old sexagesimal notation which prevailed generally before the decimal system was finally adopted.

But at night what did the Egyptians do about time measurement? They had two solutions. The priests had rather elaborate categories of stars, the positions of which told the time at a given season. This system, however, must have been so awkward because of the rapidly changing relations of solar and sidereal time that it is likely that it was used only by the experts.

The second method involved the use of the Egyptian water-clock illustrated in Figure 3. The water was drained out through a small pipe, and the form of the vessel was so chosen as to give an equal fall of water

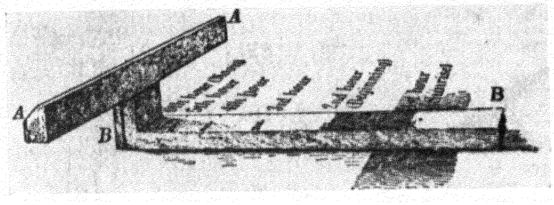

FIG. 2. *Ancient Egyptian Sun-Clock. The shadow of the crosspiece* (AA), *turned toward the east in the morning and toward the west after noon, indicated the hour on the arm* (BB). From Breasted, "*Ancient Times,*" by courtesy of Ginn and Co.

per hour. These Egyptian water clocks had enough volume to enable the water to flow all night. The Greek and Roman variants of this device, called Clepsydra, were actually used chiefly to set a limit to the speeches in the courts of justice, hence the terms *aquam dare,* to give speaking time, or *aquam perdere,* to waste time.

But in spite of the profound knowledge of stellar movement and their time-measuring capabilities herewith revealed, and in spite of the ingenuity shown by the expert in the development and perfection of water clocks, I repeat that in ancient times neither the expert nor the man on the streets had ever been introduced to time as we moderns know it. No Roman or Greek doctor ever counted his patient's pulse or took his temperature to find how sick he was.[1] Both

[1] This is strictly true with reference to the temperature but needs this qualification with respect to the pulse beat. There is evidence that the clepsydra was sometimes used by Greek doctors for pulse-counting, awkward and inexact though it was for such a purpose in comparison with our watches.

watches and thermometers came with the ushering in, some three or four hundred years ago, of a new era. In the Roman Empire the ordinary man measured time at night, as those familiar with the New Testament well know, by the first or the second crowing of the cock.

The Olympic victor led the field but nobody knew whether he won the hundred yard dash in nine, ten, eleven or forty seconds. Nowhere in the ancient world could a common citizen be late to breakfast on a cloudy morning, since without the sun there could be no definite breakfast hour. If the family planned a picnic no barometer foretold the lifting of the clouds or warned that rain was imminent. If one of the children was anemic no blood count could indicate that fact for the ancient world had no microscopes, nor telescopes either. Those were indeed simple days, for all our most important and most familiar measuring instruments, such as the clock, the barometer, the

FIG. 3. *Egyptian water-clock of the period of Amenhotep III (about B. C. 1400). The water was drained out through a small pipe and the twelve hours of the night were indicated by its level on scales inscribed on the inner face. Found in fragments in the temple of Karnak.* From Borchardt, "*Altägyptische-Zeitmessung,*" 1920, by courtesy of the Metropolitan Museum of Art.

thermometer, the telescope, the microscope, all of these first came into use in the sixteenth and seventeenth centuries A.D. Why?

Because a new conception of the significance of time began then for the first time to arise in human thought—a conception that made practically every physical constant dependent upon a time-measurement with a clock or a watch or its equivalent. Galileo, sitting there in front of his inclined plane and his marbles, and first feeling the necessity of measuring the time-rate-of-change in their positions and in their velocities as they rolled down the plane—this typifies the whole new idea, for here was laid the basis of mechanics. To lay the first stone in the foundations of that mechanics it was necessary to have a time piece, and Galileo himself is recognized as the inventor of the pendulum clock although he only used it practically, so we are told, for counting the pulse of his patients—the same patients whose temperatures he invented the thermometer

in order to be able to measure. The pulse itself, however, under normal conditions can serve, and I believe actually did serve him, as a short-interval time piece.

However, the generally accepted history of the introduction of mechanical clocks is as follows: "They seem to have begun to come into use in the thirteenth century. If invented earlier they were merely curiosities and they remained practically this until about 1600. A clock was actually put up in a former clock tower at Westminster with some great bells in 1288. These bells were sold or rather gambled away, it is said, by Henry VIII. Also a clock very much like the later pendulum clocks except that it was driven by a vibrating balance instead of a pendulum was made for the French King Charles V in 1379." About 1600 Galileo discovered the isochronism of the pendulum and although he made no practical use of it except in inventing the above mentioned instrument for measuring pulse beats, actually

pendulum clocks came rapidly into general use immediately thereafter.

But in any event the need of measuring accurately through short intervals the time-rate-of-change of position, which is velocity, and again time-rate-of-change of velocity which in its turn is acceleration, and which was found by direct experiment to be an accurate measure of force, this was the need that Galileo was the first to feel and to set carefully at work to try to satisfy; and out of it all came a whole new world concept, or better, two new world concepts, namely, first, the concept of the uniformity of nature or the concept of natural law, and second, the concept of the continuity of nature, or more specifically the concept of the necessary continuity of motion and of change of motion.

Let me try to appraise the significance for human life of the introduction of these two ideas. The first, namely, the idea of the uniformity of nature is what primarily distinguishes the modern world from the ancient.

It grew out of accurate measurements of time-rates-of-change with clocks or their equivalent, measurements the like of which were never made in the ancient world. These measurements first established certain mechanical laws which, if true, rendered the accurate prediction of some astronomical events, like eclipses, and some terrestrial phenomena, like the paths of projectiles, the stability of structures, the speeds of railway trains or airplanes, etc., a possibility. The agreement between such calculations and direct experiment is what in time has convinced the world of the essential correctness of the Galilean and Newtonian postulates, at least so far as macroscopic or large-scale events are concerned. It transformed this world from one which is at bottom capricious and animistic, as were in fact both the ancient world and the mediaeval one, to a world which is dependable, and in part at least knowable and controllable by man—a stupendous change in outlook and significant

evidence of the enormous influence of outlook on human life and conduct.

You will then agree with me that these ancient and mediaeval worlds had never, in the language of the Mad Hatter, even been introduced to Time. The vague, general, common sense notion of time that prevailed up to 1600 A.D. needed to be refined, sharpened, and rendered precise through the invention of precision time measuring instruments applicable to short time-intervals before it acquired the power to change man's thought and life and to create a modern, as distinct from an ancient or a mediaeval world.

The second element in the change in the time-concept that came in about 1600 A.D. I called above the concept of the continuity of nature. The Galilean and Newtonian world saw a constant force like gravitation producing a constant and continuous rate of change in velocity. To handle the problems of that world Newton and Leibnitz invented

the calculus which Newton christened fluxions, i.e., flowing or continuous changes. In a word, the Galilean and Newtonian world is described by differential equations, its four independent variables being x, y, z, and t, t being completely independent of anything that happens to the observer so far as x, y and z are concerned, and up to about the beginning of the 20th century this concept of time as something quite independent of space coördinates had had an enormous number of successes and no failures. Our whole mechanical world governed by mechanical laws grew out of it. To the man on the streets and to the man in the laboratory, too, it was a simple, common sense idea that a Seth Thomas clock which had been so beautifully adjusted as to come around repeatedly to 12 midnight when on successive nights a given star crosses the meridian *should tick off absolute seconds*. What more could the Mad Hatter want us to know about time than that? That was the time of the 19th cen-

tury which made all measurements depend in the last analysis upon these three absolute independent quantities, length, mass, and time.

Then came in 1887 the famous, Michelson-Morley experiment which by 1905, as soon as its experimental correctness had become recognized, spoiled all this sense of completeness and infallibility in our fundamental thinking about the absoluteness of time. What is this Michelson-Morley experiment and why has it started such a ferment in physical thinking, a ferment which seeps down to the masses and causes even the yellow journal to attempt to follow the modern developments in relativity? Let me explain it by citing a bit of history.

Throughout the whole of the 19th century we had been building up, also on the basis of the Galilean-Newtonian postulate of the continuousness of natural processes, correctly describable by an expression $\frac{dx}{dt}$ even when

the dx and dt were taken infinitely small, a wonderfully consistent "natural philosophy" as to the nature of radiant energy—a beautiful wave-theory of light—a theory too that had predicted with extraordinary success even phenomena of such analytical intricacy as conical refraction, for example. Anyone brought up as I was upon Michelson interferometers and all the manifold variety of the facts of interference in the fields of light, heat, and wireless waves, all beautifully predicted by the ether wave equations and now familiar to every fifteen-year-old wireless enthusiast, had no shadow of doubt as to the fundamental correctness of that wave theory. This theory required that it be possible, by noting the time required for a beam of light to get back to the observer when, on the one hand, it was sent forth in the direction of the earth's motion and back by reflection from a mirror to the observer, and when on the other hand it was sent a like distance forth and back at right angles to the earth's

motion, to find the speed with which the earth is moving through space. The reasoning is altogether simple and direct as the corresponding imaginary experiments with sound waves will show. Suppose a man facing east has a cliff a mile east of him and another cliff a mile south of him. If he emits a note and, while doing so, runs east to meet the echo from the east cliff he will obviously hear it a little before he receives the echo from the south cliff the distance of which from him has remained constant. This experiment so described works just as it should whether tried with sound or with light. It is essentially the way we actually do, now, measure the relative speed of approach of the earth and a star, though in this case the light is *emitted* by the star instead of being reflected from it; but this is not an essential difference as is shown by measurements on planets which shine only by reflected light. We actually measure quite accurately the rotation period of Saturn by the difference

in the relative times of arrival, or difference in wave length, of light waves coming from the limb that is moving toward us and the limb moving away from us.

But now suppose the observer and the two cliffs were on a huge moving platform travelling toward the east through still air. Then the echo from the east cliff would in this case clearly get back *after,* not before, the echo from the south cliff as can easily be seen by imagining the platform to be moving with the speed with which sound travels, for then the sound wave obviously could not reach the east cliff at all so that the echo from it would be infinitely delayed. Now in the Michelson experiment the moving platform was in fact the earth and he expected the light echo from the east cliff to get back after the echo from the south cliff. *But in fact the expected time difference did not appear.* The two echoes got back exactly at the same time. For twenty years we tried vainly to "understand" this result but we

failed completely to get a reasonable explanation of it along classical lines. *There was, and there is now, no understanding of it except through giving up the idea of absolute time and of absolute length and making the two interdependent concepts.* But this overthrows the rigidity and the theoretical perfectness of the whole of mechanics. This is why relativity interests every one. Specifically, the length of the measuring rod when it was measuring the distance to the east cliff, that is, in the direction of motion through space, was assumed by Lorentz and FitzGerald to be shorter than when the same rod was measuring the distance to the south cliff. In other words its length l depended upon the speed of its motion through space, but since speed $= \frac{dl}{dt}$ this meant that l and t, length and time, were not independent quantities. They might be considered as independent for bodies at rest or for bodies in relative motion with speeds small compared

with the speed of light, but not for bodies whose relative speeds were comparable with the speed of light.

It is indeed now no longer customary to talk about "The Lorentz-FitzGerald shortening" of the measuring rod in the direction of motion as I have done above though this is by far the simplest way of seeing the actual requirements of the Michelson-Morley experiment with respect to the space and time concepts. The reason for dropping this mode of approach is merely that Einstein in 1905 incorporated the results of the Michelson-Morley experiment into the first postulate of the special theory of relativity, that is, he generalized our experimental inability to find a speed of the earth with respect to the ether—or with respect to space if one prefers that expression—into the postulate that no absolute frame of reference for motion can be found, the *relative* motion of two bodies alone being measurable, the speed of a light signal always coming out a constant inde-

pendent of the state of rest or motion of the body on which it is being measured. This postulate, precisely like that of the Lorentz-FitzGerald shortening, denies the possibility of realizing absolute time or absolute speed and links time and space together into a composite space-time concept. So as to leave no experimental stone unturned in this most fundamental field, Drs. Roy S. Kennedy and Edward L. Thorndyke have, during the past four years, carried out and recently concluded at the Norman Bridge Laboratory at Pasadena, a most accurate modification of the Michelson-Morley experiment in which the length of the two light paths and hence the two times of travel of the two light beams are entirely different, instead of being essentially the same as they have been in all preceding repetitions of this experiment. They have thus brought forward a new and more direct and very exact experimental proof of the relativity of *time* as well as of space.

Three hundred years, then, after the first establishment of the mechanical laws upon which the modern world is built, laws which take time and space as independent variables, and which assign continuity to nature by describing her in terms of differential equations assumed to be valid no matter how small the time and space intervals are taken, these new 19th century discoveries and viewpoints begin to raise seriously the question as to whether the Mad Hatter was not right when he attributed at bottom variable, even whimsical, qualities to time.

But it is not the development of relativity so much as the development of the facts and the theory of quanta that has given Time the worst beating. The experimental discoveries of this century in the fields of photoelectric effects, Compton effects, X-ray and cosmic ray effects, and spectroscopic effects, have practically forced us to describe the physical world in terms of particles—particles or units of electrical charge which we call positive

and negative electrons, particles or units of mass which we call protons and electrons, particles or units of radiant energy which we call photons, and particles or units of action (or momentum) which we call Planck's *h* units. Such a description of the physical world cannot be made in terms of differential equations. Macroscopic phenomena, in which large numbers of these units are involved, can of course still be described in terms of such differential equations just as may the outflow of sand from a truck load of it, for here the units—the sand grains—are so small that they do not appear as such to the rough measuring instruments which we use. It is only in the field of macroscopic phenomena that the Galilean and Newtonian mechanical laws have had such amazing successes during the past centuries. But in this 20th century we have been studying for the first time microscopic phenomena, phenomena in which only one or two, or at any rate, a relatively small num-

ber of these units have been involved and in all such cases we have found the mechanical laws breaking down, thus showing *the extreme danger of extending generalizations outside the range in which observational checks have been or can be obtained.*

The final result to date of all these studies of microscopic phenomena is summed up in the so-called Heisenberg principle of uncertainty which says in essence that it is impossible to increase the accuracy of measurement of the *velocity* of a particle without by this very observational act introducing an uncertainty into the determination of the *position* of the particle, the law governing this uncertainty being that the product of the uncertainty in the measurement of the velocity (more accurately the momentum) by the uncertainty in the measurement of the position is always equal to Planck's constant h. Another way of stating the same thing is that the product of the uncertainty in the measurement of the *energy* of a par-

ticle by the uncertainty in the measurement of the *time* at which it had that energy is again equal to Planck's *h*.

From two quite different points of view then, from the observed facts of relativity and from the observed facts of quanta, the first obtained from studying bodies moving with extraordinarily high speeds, speeds comparable with the speed of light, the second obtained from studying microscopic phenomena or unitary elementary processes, physics has come to the conclusion that velocity and position, or energy and time, or more simply, length and time, are not at bottom independent of each other, in other words that there is no such thing as absolute time, nor indeed as absolute length, and therefore that in the world of *elementary* processes there is no possibility of predicting, to use now old-time terminology, what is going to happen to a particular electron, or atom, or light-quant at a particular future instant of time, from any observations of what

has happened to this electron, atom or light-quant at any preceding instant.

This means that philosophic determinism which has always been a presumptuous and a scientifically unwarranted generalization is now shown by experimental physics itself to be a false generalization. How La Place would turn in his grave if he knew what had happened to it.

Let me close with a quotation from the Oxford physicist, F. A. Lindemann.

"The recognition of the inadequacy of the old space-time coördinates has introduced a new and resilient factor into the hard and unyielding mechanism of classical physics. The harsh sequence of cause and effect has lost its power, the implacable rule of determinism its rigour. The narrow crust in which our predecessors encased our mental processes has been breached and we are entitled henceforward in the order of our physical concepts to question the grim pre-

eminence accorded by age-long consent to *Time*."

Perhaps the Mad Hatter had a reason for calling time Him.

CHAPTER II

NEW IDEAS ABOUT MATTER

FORGETTING Greek speculations, which were not based either upon accurate observational data or upon careful analytical reasoning, and which therefore had a nebulosity and a mystical generality about them quite akin to the conjectures of modern occultism or to the sweeping and uncritical assertions of both ancient and modern East Indian theosophical writing, the real development of modern atomic and molecular theory may be said to begin with the discovery of Boyle's law about 1660. As has now become well known through the well-nigh universal use of pneumatic tires, Boyle found experimentally that the pressure which at a given temperature a given weight of confined air exerts against the containing walls is directly proportional to the

density of the contained air or inversely proportional to the volume which it occupies. This result was interpreted, at least as early as 1738 by Daniel Bernouilli, in terms of the assumed motions or impacts against the containing walls of the contained gaseous particles, so that Bernouilli assumed an atomic or discrete-particle theory of the constitution of gases. This so-called kinetic theory of gas pressures was developed further by Waterson, Joule and Maxwell in England, Krönig, Clausins and Boltzmann in Germany during the middle and latter part of the nineteenth century, and by the end of that century the theory had had so many successes as to have commanded the adherence of the great majority of physicists, the two most notable quantitative evidences for its correctness having been brought forward, the first by Joule in 1851, the second by Maxwell about 1870. These two bits of evidence are worth presenting somewhat in detail.

Joule was the first to see and to prove that

it is possible to compute the actual velocities of the molecular motions from the densities of the contained gases and the observed pressures exerted by them. This possibility grew out of the discovery of what we call Avogadro's law (about 1815), a generalization from a large number of experimental facts of the following sort. Sixteen grams of oxygen confined in a given vessel are actually found by experiment to exert, at the same temperature, the same pressure as is exerted in the same vessel by one gram of hydrogen, but the atomic weight, or weight-combining power of oxygen, also is sixteen times that of hydrogen. Avogadro's generalization was then that the pressures exerted by a given number of molecules of different gases within the same vessel is independent of the type of molecule exerting the pressure; or when different gases exert the same pressures they possess the same number of molecules per cc. This actually means, if gas pressures are due to molecular

impacts, that at a given temperature each molecule hits the wall with the same striking power, whether it be a light molecule like hydrogen or a very heavy one like mercury, and this means that the kinetic energy of agitation of the molecules of gases is the same at a given temperature whether the moving molecule be a heavy one or a light one, and this means in turn that a light molecule like hydrogen, in order to have the same kinetic energy ($\frac{1}{2}\, mv^2$) as the oxygen molecule, 16 times as massive, must move just four times as fast. What Joule did, then, in 1851 was to combine this kinetic theory of gases with Boyle's law and Avogadro's rule and to deduce the actual velocities of molecular motions in gases, and the result came out most surprisingly high. According to this calculation, the hydrogen molecules in an ordinary room (and every room will have some hydrogen in it) are hitting our cheeks with the velocity of a rifle bullet from a high power gun, namely, a velocity of

about a mile a second. More strange than that, we like just that kind of treatment and complain if we do not get it. If the average energy of agitation becomes very much greater than that we feel uncomfortably warm, and if very much less than that uncomfortably cold. In a word, to revert to the language used by the physicist, the mean kinetic energy of the particles of different gases is the same whether the particle is a light one like hydrogen, or a very heavy one like mercury. This means, of course, that a given temperature in a gas means simply a given mean striking power, or kinetic energy, of its molecules no matter whether these molecules are heavy or light. All this, then, speaks strongly for a particle theory of matter.

So much for the discoveries of Avogadro, Joule and Clausins in the first half of the nineteenth century. The discovery of Maxwell, twenty years later (about 1870) is harder to describe, but it constitutes one of

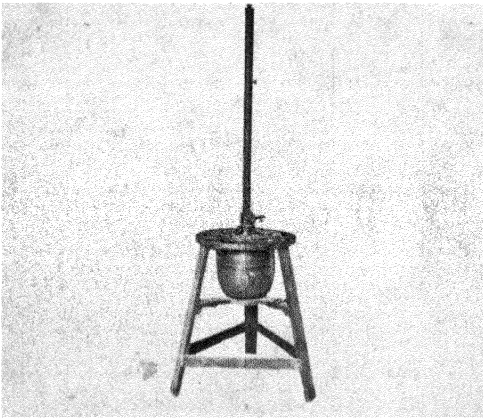

FIG. 4. *Apparatus for Experiments on "The Viscosity of Gases." The apparatus shown was constructed at King's College, London. The experiments were carried out at Maxwell's home at 8 Palace Gardens, Kensington, and led to the conclusion that "the coefficient of internal friction is independent of the density of any particular kind of gas," and "that the viscosity is directly proportional to the temperature measured from the absolute zero of the air thermometer."*

the most beautiful illustrations in history of the power of analysis to predict new and theretofore undreamed of behaviors. On the basis of the foregoing kinetic theory he computed that the viscosity of a gas should show the well-nigh unbelievable behavior of being the same at a high density as at a low one, and then he himself showed experimentally that this theretofore unknown and unexpected result is actually true. (He himself directly proved, for example, that a horizontal disk oscillating in air at 10 mm. pressure is damped down as rapidly as when the pressure is 76 cm. or even 760 cm. Figure 4 shows the historic device with which Maxwell carried out this experiment.)

Nevertheless, despite such brilliant successes of the atomic and kinetic hypotheses there were a few physicists and chemists who as late as 1900 doubted the necessity of the assumption of the discrete or particle structure of matter. Indeed, at the World's Scientific Congress held in St. Louis in 1903

a symposium on this topic was held and Professor Ostwald came from Germany to champion the view that the facts of observation could be as well accounted for by the continuous theory of the structure of matter as by the discrete or particle theory.

By 1916, however, in view—as he frankly said—of two newly discovered facts, Ostwald himself publicly abandoned his position and with this the advocacy of the theory of the continuous structure of matter entirely disappeared. These two new facts were, first, the beautiful quantitative exploration of the facts of the so-called Brownian movements, and second the definite proof of the discrete structure of electricity. These two advances are important enough to justify giving them more detailed consideration.

In 1905 Einstein was one of three men who had the penetration to generalize the conclusion reached above that at a given temperature all kinds of gas molecules possess the same mean kinetic energy of agitation

and thus to find the interpretation of the well known facts of the rapidly irregular Brownian movements of small particles suspended in liquids or gases in the general assumption that at a given temperature all bodies surrounded by gases or liquids, and hence free to move about in them, possess precisely the same mean energy of agitation or random movement as does a molecule of a gas.

This assumption was a natural enough one to make. Indeed, if, as the foregoing evidence indicates, nature is so constituted that the equality of temperature of different gaseous substances means that the molecules of these substances, whether they are as light as hydrogen or a hundred times that massive, as in the case of mercury, are knocking about and jostling against their neighbors with a given mean energy of random motion which is quite independent of the mass of the jostling particle and determined only by temperature, then it is clearly to be expected

that this will also be true when the molecules associate themselves together into larger aggregates like dust specks or minute particles of smoke or oil or water. But whether it is to be expected or not, in any case up to 1905 no one had been intelligent or able enough to make, and to work out the consequences of, this altogether general assumption that any particle of any size immersed in a fluid, whether it were the minutest of existing atoms or an object as big as a house, would be endowed, if only it had a given temperature, with one and the same average energy of jostling motion. It is to be noted, however, that since the energy of motion is governed by the formula $\frac{1}{2} mv^2$, if m the mass is in one case a billionfold that in another case the amount of movement as represented in the v^2 term must be reduced a billionfold so that no *visible* motion of objects big enough to be seen with the naked eye was to be expected, for such objects would contain a million billion molecules at least, and

hence their hypothetical trembling motions would be much too small to be visible. On the other hand, a speck just large enough to be visible *in a very high power microscope,* for example, might be expected to be seen jostling about just like a molecule, but of course with the scale of its motion enormously reduced.

This was then the qualitative explanation of the century-old riddle of the Brownian movements, a phenomenon discovered in 1815 by a Dr. Browne while observing with a high power microscope very minute particles suspended in liquids. But Einstein's quantitative prediction was that the mean kinetic energy of agitation of these particles should be exactly the same as the approximately known energy of agitation of a gas molecule. When this general prediction was carefully tested between 1908 and 1912 by carefully quantitative measurements on the Brownian movements both in liquids and in gases—in liquids by Perrin in Paris

and in gases by Fletcher and Millikan in Chicago—the observed mean measurements agreed accurately with the calculations, and the discrete or particle hypothesis thus gained another very strong support.

The last and clinching discovery which completely converted Ostwald was the definite proof in 1910 of the discrete or unitary character of electricity. The evidence here is so direct and unambiguous that it deserves especial attention in this lecture, particularly because of a later use which will be made of it. In the so-called oil-drop experiment, in which the electron—the ultimate unit of electrical charge—was isolated and its charge accurately measured, one single electron is caught alone, and at will, on an oil droplet no more than two ten-thousandths of a millimeter in radius. This oil droplet is made to float in air between two metal plates M and N (Figure 5) half an inch apart and so arranged that they can be attached one to the positive pole and one to the negative pole

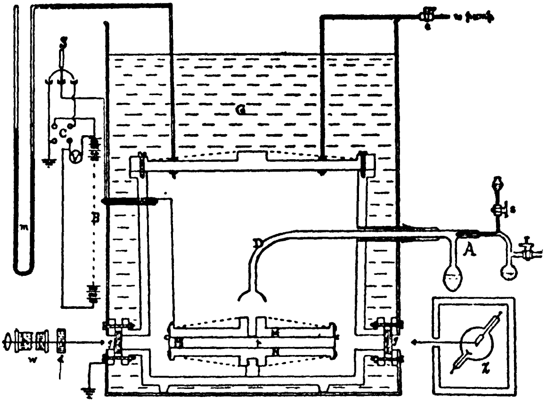

FIG. 5. A, *atomizer through which the oil spray is blown into the cylindrical vessel* D. G, *oil tank to keep the temperature constant.* M *and* N *circular brass plates, electrical field produced by throwing on 10,000-volt battery* B. *Light from arc lamp* a *after heat rays are removed by passage through* w *and* d, *enters chamber through glass window* g *and illuminates droplet* p *between plates* M *and* N *through the pinhole in* M. *Additional ions are produced about* p *by X-rays from the bulb* X.

of a 10,000 volt battery. The oil droplet there floating is rendered visible as a bright star by a powerful beam from an arc light coming in through the water cells *w d* inserted to absorb the heat from the arc. With the aid of the strong electrical field produced between the plates by this battery the exact

instant at which an electron jumps on or off the oil droplet under the influence of the X-rays from Z can be seen distinctly and accurately.

When such a single electron jumps off the oil droplet, thus leaving it completely uncharged, it fails entirely to respond to the application of the electric field and the observer knows that he is then observing a completely discharged or neutral droplet. But the instant that a new electron jumps on again the oil droplet instantly responds to the field and takes on a speed that is characteristic of the charge of one electron upon this particular droplet in such a field.

Nothing intermediate between this speed and zero speed is ever obtained, but when two or three or four electrons jump upon the same drops the speeds have the exact values 1, 2, 3, 4, etc., times the smallest observed speed. In other words, *there is nothing statistical about the charge of an electron.* Each electron possesses just that charge and

no more and no less within the limits of observational accuracy in measuring speeds, which is actually less than one per cent.

This experiment is practically equivalent to *seeing* one individual electron. The observer does not see the electron's legs move as it springs on or off the droplet, but he knows just as well as if he did see the electron itself the exact instant at which it jumps on or off by the instantaneous change in speed produced by that act, so that there cannot be the slightest doubt in this experiment that the electron is a discrete particle of electricity which may sit, and often actually does sit, alone on a droplet of a diameter of the order of a ten-thousandth of a millimeter. From the measured charge of that electron, too, all the weights of all the atoms of which the universe is built can be at once accurately computed and these weights check, too, with the results of other less accurate methods of getting at them, so that Ostwald saw at once that the discrete structure of matter

followed at once from the discrete structure of electricity.

Since about 1913, then, the discrete or particle structure of both electricity and matter has become practically universally recognized, and the theory of a continuous as opposed to a discrete structure has entirely disappeared. Indeed, nothing more beautifully simplifying has ever happened in the history of science than the whole series of discoveries culminating about 1914 which finally brought practically universal acceptance to the theory that the material world contains but two fundamental entities, namely, positive and negative electrons, exactly alike in charge, but differing widely in mass, the positive electron—now usually called a proton—being 1850 times heavier than the negative, now usually called simply the electron. The atom of hydrogen, the lightest element, contains just one proton which holds circulating about it one negative electron, the two constituting thus a

neutral system. The next heavier element, helium—atomic weight 4—has a nucleus in which four protons are held together by two electrons and the other two electrons required to make the atom neutral are circulating around the nucleus. All the heavier elements, of which there are just 92, counting hydrogen and helium, are similarly now known quite definitely to be built up out of protons and electrons, the atomic weight 238 in the case of the heaviest one, uranium, giving the number of protons in the nucleus, and the so-called atomic number, 92 in the case of uranium, giving the difference between the number of protons and electrons within the nucleus and therefore the number of negatives which must be held circulating about the nucleus to make the whole atom a neutral system.

As the evidence for the foregoing point of view became more and more convincing it looked as though the job of physics, namely, the job of finding out the nature of the

physical world, was approaching completion and that the particle theory of the structure of matter had been placed in an impregnable position.

But in all the foregoing I have said nothing about the physics of the ether, which during the nineteenth century had been becoming more and more important, quite as important as the physics of matter, since it embraced the whole of the fields of light and heat and a large part of that of electricity. And during the nineteenth century, parallel with these discoveries as to the atomic nature of matter, a *continuous theory* as opposed to a particle theory of ethereal or radiant-energy phenomena had been growing stronger and stronger. Let me trace its history as I have already done that of the theory of matter.

Forgetting as above Greek pronouncements because they were so wholly speculative, the first real "light on light" came with Newton's splitting up of white light about 1666 A.D. into the spectrum, and his

study of other phenomena of light and color. All these experiments he interpreted, primarily because of the facts of the straight-line propagation of light, in terms of a projected corpuscle or particle theory, while his Dutch contemporary, Huygens, impressed by the similarities between sound and light, advocated a wave theory of light. Nothing further either decisive or even interesting happens in this field until the year 1800 A.D. when the physicist Thomas Young in England performs a new and crucial experiment which starts the wave theory of light upon a century of extraordinary triumphs. This experiment of Young's showed that in reality there is no such thing as the straight line propagation of light, but that light is bent around an edge or is diffracted into the region of the geometrical shadow just as is sound, the sole difference, so far as this point is concerned, being that light has a wave length but about a millionth that of ordinary sound and for that reason alone is

more largely destroyed by interference beyond the limits of the geometrical shadow than is sound, and thus *appears to be* a more nearly straight-line-propagation phenomenon than does sound. Young's actual experiment was very simple. It is illustrated in Figure 6. The light from a remote slit goes through two small slits A and B parallel to the original slit but perpendicular to the plane of the paper and there is found on the screen a series of light bands at P, R, etc., with dark bands in between them. If light

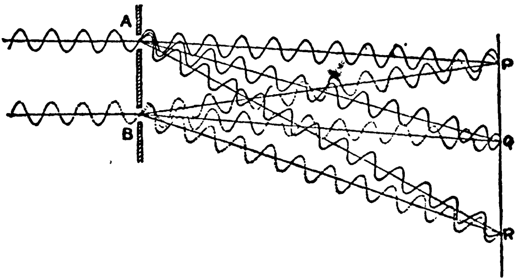

FIG. 6. *Young's Experiment. A wave passes through the two gaps* A *and* B. P *is equidistant from* A *and* B, *and the waves reinforce one another there.* Q *is half a wave-length nearer to* B *than* A, *and the waves, being there in opposite phases, cancel out. At* R, *which is a whole wave-length nearer to* B *than* A, *the waves reinforce one another again.*

is a wave motion like sound, then at a point P at which the distance AP is the same as BP the two waves, one from A and one from B, will reinforce each other and the intensity of the light at P will thus be the sum of the two equal intensities of the waves from A and B. But at a point Q, for which the distance AQ is a half wave length greater than BQ, the two waves will be in opposite phase as shown and will completely destroy each other. Again, at R where AR is a whole wave length greater than BR the two waves will again unite in the same phase and reinforce each other so that the diffraction pattern on the screen will be a series of light and dark bands. Exactly this pattern is observed in Young's experiment. It is clear that the distance between P and R is increased as the wave length is increased, since the position of R is determined by $AR\text{-}BR = \lambda$ where λ represents the wave length of the light used. Hence the diffraction pattern will be a series of lines very close together

and close to P if the wave length is very small, while the lines will be broad, far apart and extend far above and below P, into the limits of the geometrical shadow, if the wave length is large. If the two slits A and B are replaced by a series of many equally spaced slits the diffraction pattern is actually unmodified save that the points P, R, etc., become sharp images of the original slit, etc., instead of merely broad light bands shading off gradually into darker spaces between them. If the screen AB is replaced by a handkerchief, for example, in which the openings run in two directions at right angles, and if a point source, like an arc light is observed through this handkerchief the diffraction pattern actually becomes a whole series of images of A. One can usually see nine strong ones and many weaker ones. Any one can repeat substantially this experiment of Young's by holding in front of one eye a handkerchief and looking through it at a distant arc light or other point source.

The openings in the handkerchief then correspond to A, B, etc., and the retina of the eye becomes the screen on which the diffraction pattern is observed.

This experiment was quite uninterpretable on any corpuscular theory. It seemed to be interpretable only on a wave theory and it actually convinced the world of the general correctness of the wave theory of light, and during the next hundred years there developed an enormous and beautifully consistent body of knowledge which we called the physics of the ether. It incorporated successively into itself first light, then heat, then the whole of wireless waves, then ultraviolet light, then X-rays, then cosmic rays, all of these being successively and definitely shown to be phenomena of exactly the same sort save for the one element of wave length, which moves continuously from exceedingly long values in wireless waves up through the progressively shorter wave lengths of heat, light, ultraviolet, X-rays, gamma rays to cos-

mic rays of unbelievably short wave length and almost infinite frequency. The frequency of visible light is a hundred million times that of ordinary wireless waves of 50 meters wave length, while the frequency of the cosmic rays is a hundred million times that of visible light.

So the nineteenth century actually built up for us two different worlds, one the world of matter composed of discrete particles and the other the world of ether physics governed by the principle of continuity with its wave interpretations, and we had criteria by which we could tell to which world a given phenomenon belonged. Thus the beta rays and the alpha rays from radio-active substances, for example, were found to be deflectable by a magnetic field as they should be if they consist of streams of electrically charged particles, whereas light and gamma rays from radium were completely uninfluenced by a magnetic field (see Figure 7), a characteristic possessed by all ether rays.

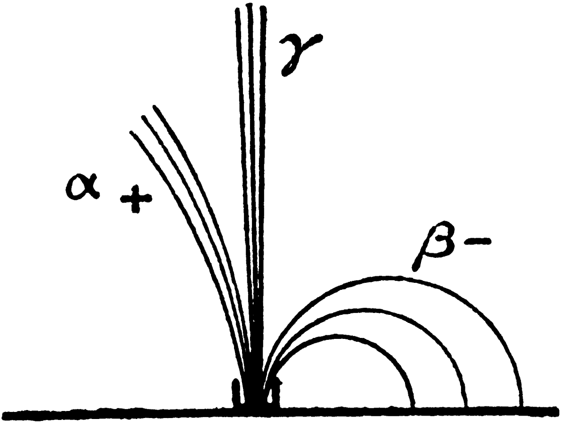

FIG. 7. *This figure illustrates the difference in the behaviors in a magnetic field of alpha, beta, and gamma rays from radium. The lines of force of the magnetic field are supposed to run perpendicularly to the page. The alpha rays, heavy and positively charged, are deflected in one direction, the light negatively charged beta rays in the other, while the gamma rays are like light in being entirely uninfluenced by the magnetic field.*

Hence alpha and beta rays took their places as streams of projected material particles, while light, which was not deflected by a magnetic field and which showed these diffraction effects, was certainly an ethereal phenomenon, and in 1912 X-rays and gamma rays were definitely thrown into the field of

ether physics by Laue's experiments, which showed not merely that these rays are uninfluenced by a magnet, but also that diffraction patterns just like those produced when light goes through a handkerchief could be obtained by passing X-rays, and later gamma rays, through a crystal lattice, essentially like a handkerchief, except that the openings are very much closer together in a crystal than in a handkerchief. The wave length of X-rays was computed from the spacing of the crystal lattice and of course came out very small compared with the wave length of light, in fact about a thousandth as great.

So long as the two worlds—the particle world and the ether world—could be kept separate all went well, but these two worlds have recently begun to rebel at being kept apart and the rebellion has now become terribly interesting and important. Let me give the steps in the rebellion and then the results to date.

First, in the working out of the so-called

photoelectric effect in the first two decades of the twentieth century we found definitely that waves were acting in this effect not like waves but like bullets of light or light-darts, like particles. The significant experiment consists in measuring the energy with which an electron is jerked out of a metal surface, for example, first by light of varying intensity but constant frequency, and second by light of different frequencies or colors. By 1916 the experimental study of this effect had shown definitely that the light-dart or photon theory alone here holds. In other words, in this effect the energy of the light wave travels through space as a localized bundle, i.e., as a discrete particle, and the amount of energy in each light-dart or light particle is proportional to its frequency ν or is equal to $h\nu$, in which ν represents frequency and h is the so-called Planck's constant. This result was first obtained sharply and altogether unambiguously in experiments done in the Ryerson Laboratory

in 1913-1914, though as early as 1900 Lenard in Germany had made experiments which suggested this light-dart theory and Einstein had definitely postulated it in 1905. In these 1914 experiments the energy with which electrons were jerked out of the alkali metals by monochromatic light of different wave length was accurately measured and found to be completely independent of the intensity of the light, an amazing result since the energy of a wave necessarily dies down with distance from the source. Also equally amazingly, these photoelectric experiments showed that the energy of electrons jerked out of metals by light of different colors, i.e., of different frequencies, were directly proportional to the incident frequency, blue light throwing out electrons with about twice the energy of red light. These results could apparently only be interpreted on the assumption that *bundles of light energy hold together as they shoot through space,* and that each individual

light-dart carries an energy which is proportional to its frequency.

To find thus experimentally that the energy of a single ray of light was independent of its intensity and proportional to its frequency was terribly upsetting to all existing theories. When these facts were first brought to light they seemed the most amazing con tradiction ever revealed in the history of physics. Then after the war we found by new experiments by de Broglie in France and Ellis in England that the same results hold for X-rays and for gamma rays. Figure 8 is an actual photograph which shows clearly this relationship in the case of X-rays.

FIG. 8. *Long tracks with large forward component. Sphere tracks. Cylindrical X-ray beam, 0.5 mm. in diameter, has traversed 8 x 10^3 cm. copper. Final pressure 19 cm.*

The X-ray beam shoots through the air chamber from the right and jerks in succession four electrons out of the molecules of the air. That these electrons all possess the same energy, $h\nu$, can be proved by measuring the total length of each track, or better, the total number of ions produced by each. That these ethereal light-darts possess momentum too is indicated by the fact that they drive the electrons forward in the direction in which they themselves are going. Lately we have found by actual photographs of cosmic rays, taken in the Norman Bridge Laboratory, that they, too, act like light-darts. There seems to be no uncertainty about it. Also in the year 1923, A. H. Compton proved definitely that when such a light-dart, now called a photon, hits a free electron the laws of encounter that govern the impact of two billiard balls is obeyed, thus giving another proof of the particle as distinct from the wave theory of light. When we are dealing, then, with *elementary* processes,

such as encounters between one individual light-dart and an electron, ether waves always act like discrete particles or bullets of energy shot through space with the speed of light. But how could this be reconciled with interference experiments like Young's? Nobody could see the answer. Maybe the physical world is not so simple after all.

But now we come to the most amazing discovery of all. During the last four years some new experiments have been performed, first by Davidson and Germer at the Bell Laboratories in America, then by G. P. Thomson in England, then by Otto Stern in Hamburg. These may be summarized in the two statements, first, that a narrow *stream of particles* like electrons can be made to show all the interference effects of a narrow beam of light or of X-rays; and second, that a linear stream of atoms following one another in very rapid succession also show the precise interference effect exhibited by light rays. *In other words, not only may*

waves be made to show all the properties of particles but particles may also be made to show all the properties of waves. This is one of the most amazing situations ever encountered by any science. That it is completely established experimentally is shown by the three following pairs of photographs. The first, Figure 9, is Frederick and Knipping's diffraction pattern obtained by passing X-rays (ether waves) through a crystal of zinc blend parallel to the trigonal axis of the cubic crystal. Its mate, Figure 10, on the other hand, is the diffraction pattern obtained by G. P. Thomson in 1928, by passing a beam of electrons, that is a beam of cathode ray *particles,* through a very thin film of crystallized aluminum.

Again, Figure 11, shows another of Frederick and Knipping's X-ray diffraction patterns obtained by passing X-rays through a crystal of zinc blend parallel to a cubic axis of the crystal, while Figure 12 is a quite similar diffraction pattern obtained by S. Ki-

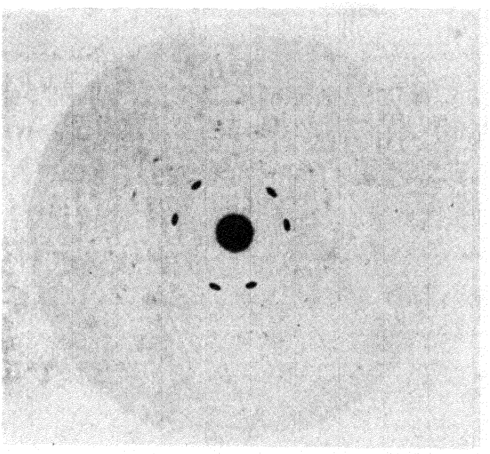

FIG. 9. *Diffraction pattern produced by passing a narrow beam of X-rays (ether waves) through a thin crystal of zinc blend parallel to the trigonal axis.*

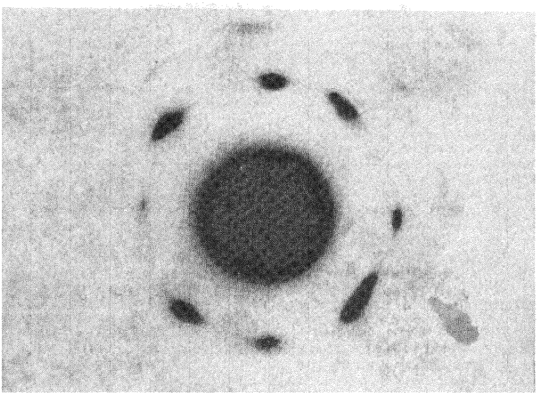

FIG. 10. *Diffraction pattern produced by passing a narrow beam of electrons (particles) through a thin film of crystallized aluminum.*

kuchi of Japan, by passing a beam of electrons *(particles)* through a very thin mica crystal.

Finally, Figure 13 is an X-ray, that is, an ether-wave, diffraction figure such as is always produced by a powder or a thin film in which the elementary minute crystals have not a regular, but rather a wholly random orientation, and Figure 14, is the corresponding diffraction pattern obtained when a beam of electrons *(particles)* passes through thin gold foil in which the rolling or beating has given the elementary crystals again a random distribution.

Why have these contradictions arisen? Can we see even dimly a physical significance behind them? For, to the experimental physicist, at least, this world is at bottom more than a world of equations or even of ideas. Some external physical things are happening and we cannot rest indefinitely content with two types of physical interpretation of the same phenomena that

seem to be mutually exclusive. The ultimate *elementary processes* which constitute light cannot be both waves and corpuscles. Which are they really? and what kind of legerdemain has nature played upon us to make them seem otherwise? How "did the rabbit actually get into the hat?" The only way I can see out of the contradiction is to assume that all microscopic or elementary processes, whether they are processes of matter physics or of ether physics are at bottom discrete-particle-processes, the four types of units involved being (1) elementary units of electrical charge, (2) elementary units of mass, (3) elementary units of radiant energy, and (4) elementary units of action (called Planck's *h* units). Only when large numbers of these units are involved do we get over into the field of *continuous* processes of which waves constitute one of the best of examples. In other words, all apparently continuous phenomena represent statistical or mean behaviors of elementary

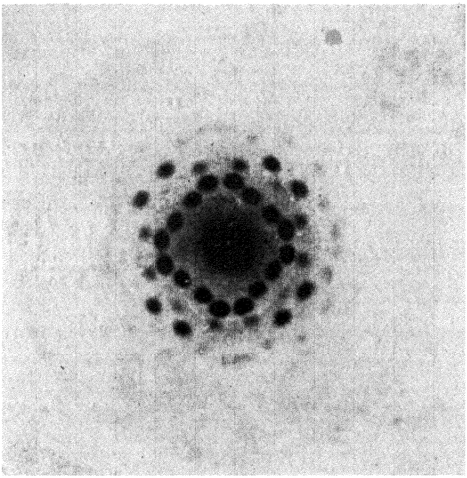

FIG. 11. *Diffraction pattern produced by passing a narrow beam of X-rays (ether waves) through zinc blend parallel to a cubic axis.*

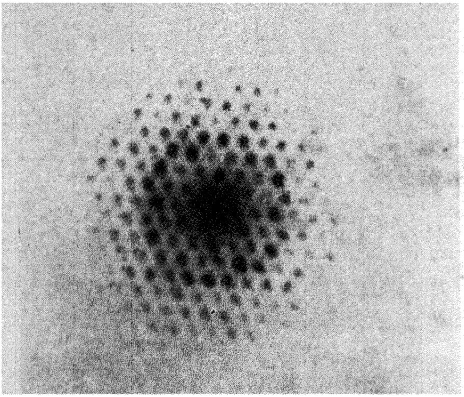

FIG. 12 *is the quite similar diffraction pattern obtained by passing a beam of electrons (particles) through a thin mica crystal.*

particles, in precisely the same way as the temperature of a mass is the mean kinetic energy of its particles, which obviously does not imply that every individual molecule has that energy. We practically know, for example, that when one single electron hits a fluorescent screen it makes at a particular point one single scintillation. When, however, a lot of them go through two holes side by side for some reason they distribute themselves so as to make the wave pattern which we actually observe.

The question as to just why they do this is most interesting and the present effort of physicists is to find the reason in the Heisenberg uncertainty principle, i.e., an uncertainty, or better an incorrectness, in the assumption of an absolute length and an absolute time. The probability function which in some cases comes out of the Heisenberg equation has already succeeded in predicting the wave equation which yields the observed interference pattern, all of

which seems to show that the long tyranny of the two absolute despots space and time is at an end, and the rule of the new joint concept of space-time is better suited to our modern conditions.

But this history that I have tried to recount shows that we are moving on and on continuously in our knowledge of the behavior of the physical world. We first discover the laws that govern the interaction of large bodies, Newton's laws, and these are just as valid now for large bodies as they ever were; then we discover the laws that hold in all the large-scale phenomena of ether physics, and they too are just as valid now as ever for these large-scale phenomena. Then we discover methods of pushing our researches farther into the field of *elementary processes* and a whole group of new laws appears not irreconcilable with the first but *containing the first as limiting cases as the number of units involved becomes large.* In other words, when we are buying sand by the ton

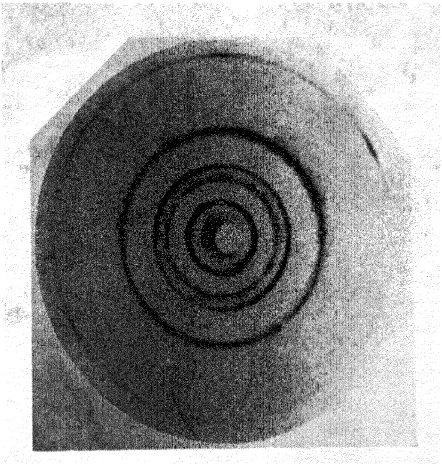

FIG 13. *X-ray (or ether-wave) diffraction figure produced by a powder or thin foil in which the elementary minute crystals are distributed at random.*

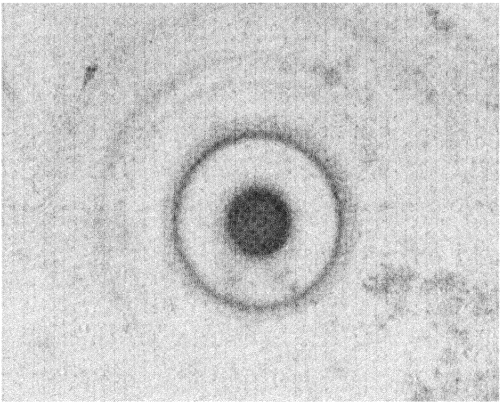

FIG. 14. *The corresponding diffraction pattern obtained when a beam of electrons (particles) passes through thin gold foils in which the elementary gold crystals again have a random distribution.*

we do not even need to know that it contains grains. And so long as we are merely building houses we get along all right without the knowledge of the granular structure. But fortunately the mind of man is not content with merely building houses. It seeks to "*know* so that life may be enriched."

CHAPTER III

NEW IDEAS ABOUT VALUES

JUST a hundred years ago my grandfather, one Daniel Franklin Millikan, decided to leave the farm in the Berkshire hills near Becket, Massachusetts, which for seventy years had been the ancestral home of the Millikan family and to try his fortune in the newly opened and less rocky lands of the Western Reserve in Ohio. There my father was born in 1834, and when he was four years old the family took its Lares and Penates, its horses and cattle, and treked westward again in covered wagons to settle this time on the banks of the Rock River not far from the present town of Sterling, Illinois.

I mention this because the conditions of that migration, the motives prompting it, the mode of travel of the emigrants, their va-

rious ways of meeting their needs and solving their problems, their whole outlook upon life, were extraordinarily like those which existed four thousand years earlier, when Abraham trekked westward from Ur of the Chaldees. In a word, the changes that have occurred within the past one hundred years, not only in the external conditions under which the average man, at least in this western world, passes his life on earth, but in his superstitions, such as the taboo on the number thirteen or on Friday-sailings, in his fundamental beliefs, in his philosophy, in his conception of religion, in his whole world outlook, are probably greater than those that occurred during the preceding four thousand years all put together.

It is my purpose tonight to try to analyze these changes, to see what fundamental influences have brought them about, and to let you know what, from the standpoint of one particular physicist, they seem to mean in their relation to his own life and conduct

and, perhaps to some extent, to the life and conduct of all of us. I realize full well that this is a bit presumptuous since the very fact of my doing it may seem to imply that my analysis is better than some one else's and my conclusions sounder. This will be true only in so far as my analysis and my conclusions relate to the field in which I may have some special knowledge, but I know of no way in which we can improve our *common* outlook save by this swapping of ideas or in some way getting a composite of the pictures taken from our individual specialized standpoints, and seeing what comes out as of common significance. If you will look upon what I have to say, then, merely as my personal outlook, to be compared with many others before any common judgment can be reached, this talk will have served its purpose.

These stupendous changes of the last century in our physical lives, our beliefs, and our motivations have all been brought about

in the last analysis, I think, by new knowledge of the universe around us. Some of this knowledge is in fact centuries old, but new in the sense that it has heretofore been the knowledge of the few, and has only recently become widely spread and hence influential in modifying belief and conduct. This spreading has itself been due to the stupendous extension and improvement of the means of disseminating knowledge, an improvement which is itself a part of the new knowledge. I shall, therefore, divide my subject into two parts and discuss, first, the origin of the knowledge, the dissemination of which has recently been so significant, and second, some very recent advances the knowledge of which is not yet widely spread, but which may be most significant, both for the present, and for the future.

In a paper published in a volume by Scribners under the title, *Science and the New Civilization,* I have classified the three great elements in human progress as

1. The Discovery of the Golden Rule—a supreme contribution of moral and religious thinking, and therefore properly called, I think, a contribution of religion to the progress of mankind;
2. The Discovery of the idea of Natural Law or of the Uniformity of Nature; and
3. The Discovery of the Idea of Progress or of Age-long growth or Evolution.

The last two may be fused into one under the title, the discovery of what I shall call "the scientific method," since both of them arose from it, so that in my classification religion and science become the two great sister forces which have pulled and are still pulling mankind onward and upward. And the two are necessarily intimately related, for the primary idea in religion lies in the single word "ought"—the sense of duty being underneath all religion, while what is duty, that is, what particular line of conduct is actually best for society as a whole must be

determined by science; in other words, this is a question of knowledge or intelligence, rather than of conscience. I am thus using the two words conscience and knowledge as at least very closely related to the words religion and science.

But for the sake of what follows, I wish to go a step farther, for someone asks, where does the idea of God come in? Isn't it a part of religion? Yes, I think it is, because I do not see how there can be any sense of duty, or any reason for altruistic conduct which is entirely divorced from the conviction that moral conduct or what we call goodness is somehow or other worth while, that there is Something in the universe which gives significance and meaning, call it value if you will, to existence, and no such sense of value can possibly be in mere lumps of dead matter interacting according to purely mechanical laws. Job saw thousands of years ago the futility of finite man's attempting to *define* God when he cried, "Can

man with searching find out God?" and, similarly, wise men ever since have always recognized their own ignorance and finiteness and have been content to stand in silence and in reverence before Him. Einstein in a recent article has written, "It is enough for me to contemplate the mystery of conscious life perpetuating itself through all eternity, to reflect upon the marvelous structure of the Universe which we can dimly perceive, and to try humbly to comprehend even an infinitesimal part of the intelligence manifested in nature." I myself need no better definition of God than that, and some such idea is in all religion as a basis for the idea of duty. So with these words of explanation, I shall launch into my attempt to present the new knowledge that has come to us about the universe around us and its influence upon the living and thinking of our times.

I think there can be no shadow of doubt that the great characteristic feature of our

times, the one thing that distinguishes our civilization from all that have preceded, is the discovery of the scientific method and the results that have followed upon its application. That discovery was made some three hundred years ago, but its cumulative effects have come only within the last century. But just what is the scientific method and what was the change in mode of approach that Galileo so conspicuously employed and which resulted in what Whitehead calls "the most intimate change in outlook which the human race had yet encountered"?

The method consisted in discarding all *a priori* postulates about the nature of reality and all complete philosophic schemes, such as all the philosophers of the ancient world, idealists and atomists alike, had started with, and quarrelled interminably over, discarding, likewise, all intuitive axioms on the one hand and authority on the other such as had been the foundation of medieval scholas-

ticism, and appealing by the experimental method, as Dampier-Whetham says in his *History of Science,* "to the tribunal of brute facts—facts which bore no relation to any philosophic synthesis then possible. Natural science may use deductive reasoning at an intermediate stage of its enquiries, and inductive theories are an essential part of its procedure, but primarily it is empirical, and its ultimate appeal is to observation and experiment. . . ." "It is not too much to say that Galileo started modern physical science on the course which has extended unbroken to our own day. In a very real sense, he is the first of the moderns: as we read his writings we instinctively feel at home, we know that we have reached the method of experimental science which still is in use today. The old assumption of a complete and rationalized scheme of knowledge . . . has been given up. Facts are no longer deduced from, and obliged to conform with an authoritative and rational synthesis as in scholas-

ticism, no longer are they given meaning, thereby, as they were even in the mind of Kepler. Each fact acquired by observation and experiment is accepted *as it stands,* with its immediate and inevitable consequences, irrespective of the human desire to make the whole of nature at once amenable to reason. Concordances between the isolated facts appear but slowly, and the little spheres of knowledge surrounding each fact come into touch here and there, and perhaps coalesce into larger spheres. The welding of all knowledge, scientific or philosophical, into an all embracing unity, if not seen to be forever impossible, is relegated to the distant future. Medieval scholasticism was rational; modern science is in essence empirical. The former worshipped the human reason acting within the bounds of authority; the latter accepts brute facts whether reasonable or not."

Galileo, unlike some who followed him and founded systems upon his work, like the French encyclopaedists of the eighteenth cen-

tury, "was content to wait in acknowledged ignorance upon questions that cannot be answered by rash speculation or deduced from philosophic systems. He confessed that he knew nothing about the nature of force, the cause of gravity, the origin of the Universe. Rather than express extravagances he declared it better to pronounce that wise, ingenious and modest sentence, 'I know not.' "

That is the method of science. Now what has resulted from its application?

First, practically the whole of modern material civilization in so far as it differs from ancient civilizations. It is easy to trace the pedigree of practically every modern industrial or scientific device back to the new knowledge which Galileo's method and indeed his own experimental researches began to bring to light. Let me give just two illustrations.

For thousands, perhaps for tens of thousands of years before his time, men had pushed carts and pulled wagons, but not one

of them had any correct idea about the exact relation between the force exerted and the motion produced. This is just what he found by studying the way his marbles acquired velocity as they rolled down his inclined plane. Without the formula, force equals mass times acceleration, which came into the knowledge of mankind through his work, not a single steam engine, automobile, airplane, or any other power machine could be designed today.

Further, it was precisely this formula which seventy-five years later in the hands of Newton made the discovery of the law of gravitation possible, and with it the whole development of celestial mechanics, the successes of which have at last weaned the whole world away from treating with anything but ridicule "the village that voted the earth was flat, flat as my hat, flatter than that" (Kipling), and opened the eyes of the world to the glories and the mysteries of modern astronomy.

Again, through hundreds of thousands of years, alike in the epochs of savagery and barbarism, and in those of amazing Greek and Latin civilizations, man had warmed himself at his camp fire and his grate without ever stopping to wonder what heat was; or, if he wondered, he had no idea how to set to work to find out. More than that, it was impossible for him to find out before the idea or concept of *energy of molecular motion* had been formulated, and this idea came directly from Galilean and Newtonian mechanics. It was 1850 before the word "energy" as a sharply defined physical concept came into use at all, and it was only then by following exactly the method of Galileo and also by using directly the results of his and Newton's work that the foundations were laid by Joule and Kelvin in England and by Clausius and Helmholtz in Germany, for the modern development of the steam engine, which utilizes the relations between

heat and work, and which begot in its turn the internal combustion engine.

In exactly the same way through Franklin, Volta, Faraday, and Maxwell, all utilizing the method as well as the results of their scientific ancestors, has the age of electricity within my own life time been ushered in. Also, the same method applied to the study of the earth's crust with its fossil records of age-long development from lower to higher biological forms and the further study of the anatomical relations between these forms have brought to light brute facts which must tell their own tale no matter what preconceived philosophies or world-systems they may encounter. This whole group of observed facts about the universe around us is what is responsible for the enormous change in human outlook that has been characteristic of our century. But when I talk about change in human outlook I have left the field of merely material changes and have touched the second advance, more important

than the material one, which came as a result of the application of the scientific method. Let me follow it a little farther.

Through all primitive thinking, and some of it not so primitive, nature is regarded as essentially capricious. Things happen because the God of the mountain, the forest, the river, or the sea wills to have them happen, and that God is in general endowed with practically all man's frailties. That God's will can be supplicated, pleased, enraged, appeased, cajoled, but that it operates in any systematic way or in accordance with fixed principles which man by study can come at least in part to understand, that was an idea which, while it was adumbrated in the Greek world, notably in the work of Aristarchus of Samos, Archimedes of Syracuse, and Hipparchus of Alexandria, was after all practically without influence in human life before the real advent of the scientific method in the sixteenth and seventeenth centuries. Galileo in establishing the laws

of force and motion assumed the principle of uniformity and laid down regularities or laws which made prediction of astronomical events and of some terrestrial events a possibility. The continued and ever increasing success of these predictions soon began inevitably to change men's thinking about the fundamental nature of the universe. With increasing knowledge, men's ideas of God, the integrating factor in the universe, of course began to change. The days of child-like anthropomorphic conceptions began to draw to a close, and mankind began to move forward to a finer, bigger, more mature, more satisfying conception. A God of caprice and whim began to be replaced in human thinking by a God who rules through law, a universe which was not worth knowing because it could not be counted upon began to be replaced by a nature which is dependable and to some extent at least understandable, even controllable by man.

With the advent of this idea man began to

be no longer merely a plaything in the hands either of blind fate or of a capricious deity, but himself a vital agent in the march of things. His conception of duty and therefore religion began to change. Under the old conception his chief duty had been to propitiate his God, hence monasteries, penances, withdrawal from the world, and all that goes with them. Under the new conception duty came to be to try to understand God's laws, and to bring one life and the lives of mankind in general into harmony with them. Most important of all, in the old days men had made a wholly artificial and irrational distinction between the natural and the supernatural. Events which were sufficiently common and familiar were thought of as natural, and events which were uncommon and not understood were called supernatural. The idea of the uniformity or repeatability of events abolished completely all such child-like distinctions. All events without exception came to be worthy of

study and of attempts at understanding, because nature is assumed to be dependable, not capricious. Familiarity or unfamiliarity have nothing whatever to do with it. Call all events natural if you will, or all supernatural if you prefer, but forget, so says Galileo's method, either one term or the other. No wonder Whitehead called it "the most intimate change in outlook the human race had yet encountered." That is, I think, what has brought about the stupendous change in point of view of the past century.

And note well this, that practically all the men who introduced these changes into human thought and life regarded themselves as essentially religious men. Let me show why I say that. Dampier-Whetham says in his *History of Science,* "We must remember that all competent men of science and almost all philosophers of the middle of the seventeenth century looked on the world from the Christian standpoint. The idea of an antagonism between religion and science

is of a later date." Leonardo da Vinci, a century earlier than Galileo, but completely modern in his scientific viewpoint, though not historically influential because he did not publish his work, which has only recently come to light through the discovery of his note book—of him his biographer writes, "His own philosophic position seems to have been an idealistic pantheism, in the light of which he saw everywhere the living spirit of the universe. Yet with the fine balance of a great mind he saw the good beneath the load of inconsequent evil and accepted the essential Christian doctrine as an outward and visible form for his inward spiritual life." Or again take Newton, whose chief work, the "Principia," Lagrange, the greatest of French mathematical physicists, described as "the greatest production of the human mind," and who called Newton himself not only "the greatest genius that has ever existed" but also, "the most fortunate, for" says he, "there is but one universe, and it can happen

to but one man in the world's history to be the interpreter of its laws." This same Newton wrote in his "Opticks," "The main Business of Natural Philosophy is to argue from phenomena without feigning hypotheses and to deduce causes from effects, till we come to the very first Cause, which certainly is not mechanical." "To Newton," says Dampier-Whetham, "God is imminent in nature."

Robert Boyle took essentially the same position and Sir Francis Bacon, completely modern and scientific in his viewpoint, says, "I had as soon believe the fables of the Talmud and El Koran, as to think that this universal frame is without a mind." That is only another way of saying precisely what Einstein said in the foregoing quotation. Similar quotations might be made from Franklin, Faraday, Kelvin, Maxwell,[1] Ray-

[1] Mr. P. G. Tait, who writes for the Britannica the biographical article on Maxwell says therein, "Though perfectly free from envy or ill will he yet showed on fit occasion his contempt for that pseudo-science which seeks for the applause of the ignorant by professing to reduce the whole system of the universe to a fortuitous sequence of uncaused events."

leigh down to Eddington and Jeans of today, all showing that while new and broader conceptions come inevitably into philosophy and religion as science advances, there has been no conflict between the two as interpreted by the best minds the world has produced.

Now this whole group of ideas which has been developed by the world's thinkers and leaders from the times of Leonardo da Vinci and Galileo down, has become widely disseminated in our western world relatively recently, and has been the chief cause of the change in intellectual outlook, in religious thinking, too, that has taken place in America during the last century. Incidentally, it is interesting to inquire, especially in view of the statements that one so often hears, whether the dissemination of scientific ideas in this century has actually weakened the hold of essential religion, or even organized religion in the United States. Here are some statistics which in a careful study, Mr. Charles Stetzle published in 1928 in the

World's Work. In the year 1800 seven out of every one hundred of the population in the United States were Protestant church members, in 1850 fifteen out of every hundred, in 1900 twenty out of every hundred and in 1926 twenty-six out of every one hundred. In other words, during this nineteenth century when these changes were going on, the Protestant churches gained three and a half times as fast as the population, and during the last twenty years the Protestant churches made a net increase in membership of 46% while the population in these same twenty years gained by 36%. Other extraordinarily interesting statistics have recently been collected by Harvey C. Lehman of Ohio State University and Paul A. Wilty of Northwestern University and published in the *American Journal of Psychology,* October, 1931, vol. 43, pp. 664-678. These men have gone through the 1926-27 edition of *Who's Who in America,* and found that 25.4% of the group of 1,016 listed "distin-

guished scientists" report themselves as church members, or about the same as the percentage of the whole population found on the rolls of the Protestant churches. This appears to show that in this particular scientists are not appreciably different from the rest of the population. But it is when the authors divide up their material on the basis of age that they find the most interesting averages, namely that while only about 12% of the oldest fourth of the scientists list themselves as members of churches, 44% of the youngest fourth so record themselves. In other words, contrary to current opinions, in so far as church membership is taken as a criterion, it is the old birds that seem to need watching, not the young ones. As the older group disappears the figures indicate that the coming years may be expected to show increasing, rather than decreasing relations between the scientists and the churches.

There is no indication, then, in any of the foregoing figures that in this country the

march of science has undermined during the past century, or is now undermining, protestant religion, and it certainly should not undermine any religion which is capable of adapting itself to new conditions and keeping in step with the march of knowledge, and any other sort of religion probably ought to be undermined.

As soon, however, as man, be he scientist or cleric, deserts the method of science, a clash may appear and there is one historic instance of such a desertion which deserves attention here.

The principles governing the motion of inert bodies under the influence of their mutual gravitational forces as worked out by Galileo and Newton, were found sufficient to explain all the majestic motions of the heavenly bodies. These two minds were great enough deliberately to refuse to build up philosophies beyond the reach of their observed facts, Newton himself pointing out that the cause of his gravitational force re-

mained unknown. When, however, the discoveries of Galileo and Newton got over into France, the French philosophers of the eighteenth century, forgetting that the essence of the scientific method lay in sticking close to the observed facts and not asserting knowledge beyond the range of observation, yielded to the lure of such inclusive generalizations as had rendered Greek philosophy impotent and proceeded to convert Galileo's and Newton's science into a mechanical philosophy in which the whole of the past and future was calculable from the positions and motions of inert "material" bodies and man became a machine.

This crude materialism, sometimes called scientific but in its very method and essence unscientific because universally assertive and dogmatic, had an influence on the early history of this country, which borrowed much of its thinking from eighteenth century France, and while clear-thinking minds in all countries refused to be stamped by it,

realizing the limitations of the scientific method and differentiating sharply between determinism in science as a convenient, indeed a necessary, working hypothesis, and determinism as a general philosophy, yet "to minds more logical than profound" the inference from science to philosophy seemed inevitable, and this movement continued strong throughout the nineteenth century, especially in Germany, until beginning with the last decade of the nineteenth century experimental physics itself threw this philosophy out of its house root and branch.

And here I come to the newer facts of the universe around us which have quite recently taught all physicists, and all mankind I hope, that the road to fruitful effort lies in sticking close to the scientific method and avoiding extending generalizations into fields beyond those in which experimental observations have demonstrated their validity, the method of recognizing and being guided by brute facts whether these fit into

general philosophies or not. Eighteenth and nineteenth century materialism assumed that the universe might be interpreted in terms of a fixed number of unchangeable atoms, and then brute facts were found which showed that some of these atoms were changing continuously into other atoms and the dogma of the immutable elements was gone. Then materialism assumed that the universe could be accounted for in terms at least of the motions of *"material"* particles of some kind, and then brute facts were found which showed that matter could disappear into radiant energy or ether waves, and the dogma of the conservation of matter was gone, and with it the excuse for the very name materialism. Then, again, materialism assumed that the universe could be accounted for in terms of Galilean and Newtonian mechanical laws, which in large-scale phenomena had always been found to work. Then brute facts were found having to do with specific heats at low temperatures for

example, where the laws of Galilean and Newtonian mechanics simply did not work at all and the dogma of the universality of the mechanical laws was gone. Then materialism assumed the universality of the electro-dynamic laws and presto a region was found having to do with spectroscopic and X-ray phenomena in which these did not work and another dogma blew up. Then materialistic philosophy asserted that light must be ether waves or corpuscles. It was inconsistent or unintelligible that it could be both, and again brute facts appeared which showed that, whether it was intelligible or not, light acts at one and the same times like both waves and corpuscles, and now every physicist is accepting these apparently contradictory facts and making the most of them. Then materialism assumed that because the laws of interaction of bodies at slow speeds had been verified they would also hold for high speeds, and brute facts appeared which denied the validity of this

generalization and in the denial gave birth to the theory of relativity.

Result, dogmatic materialism in physics is dead! If we had all been as wise as Galileo and Newton it would never have been born, for dogmatism in any form violates the essence of the scientific method, which is to collect with an open mind the brute facts and let them speak for themselves untrammeled by preconceived ideas or by general philosophies or universal systems.

Now, if anybody here is bothered by the reconciliation of free will and determinism, I shall be glad to state for him my own position, as follows: Practical free will, or the sense of responsibility, is to me a brute fact given by direct experience. It is of course true that, strictly speaking, the only absolute knowledge that any of us has is the knowledge of his own sensations, and my free will is based upon that sort of knowledge. Most of the so-called knowledge that we act upon, including our scientific knowledge, is

not of that sort. It is rather *evidence* that by long experience of our own or of others we have come to trust as a safe guide to conduct because within the range of such long experience it has been found to work. The hypothesis of determinism within the range of macroscopic or large-scale physical phenomena has been thus far found to work, and it therefore represents such knowledge. In certain microscopic or elementary processes its correctness even in purely physical processes has been questioned by physicists. I refer, of course, to the Heisenberg principle of uncertainty, but this raises no questions whatever with respect to any of the phenomena of large-scale physics or its applications, that is, these phenomena are consistent with the working hypothesis of scientific determinism as the physicist has always used it. Metaphysical or philosophic determinism I am not in the least interested in, because it represents one of those sweeping generalizations, or assertions of universal validity even

when fields are entered outside those within which by a long process of prediction and experimental check the principle in question has been found to be a useful and dependable working hypothesis. It is precisely at this point, that is, in making such unwarranted extensions of his laws, that the physicist has stubbed his own toe over and over again within the past forty years, and I think he has now learned his lesson and will not make that sort of mistake again. The dogma of philosophic determinism has been adopted by religious and unreligious groups alike, by Calvinists and by French and German "materialists" (so-called). To me philosophic determinism is a pure dogma of no particular interest to the man who has even scented afar the scientific method. Scientific determinism, as we use it in physics, is merely a convenient working hypothesis, certainly no more difficult to reconcile with free will than are the wave properties of electrons and photons difficult to reconcile

with their corpuscular properties. We physicists have not yet reconciled in any physical sense these apparently mutually exclusive properties. We have merely kept our minds humble, our consciousness of ignorance and finiteness strong, and have bowed before brute facts. A man may call himself a determinist if he will, but if he at the same time keeps his conscience, that is, his sense of social responsibility, vigorously alive, he is pretty certain to be an essentially religious man, for "What doth the Lord thy God require of thee but to do justice, to love mercy, and to walk humbly with thy God."